Analysis of Lake Evaporation at Lake Tahoe, California/Nevada, USA

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Outline

- Study Site Details
- Motivation for the Study
- Methodology
- Results and Discussion
  - Diel and Daily
  - Monthly
  - Seasonal
  - Annual
- Conclusions

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Study Site Details

❑ Details

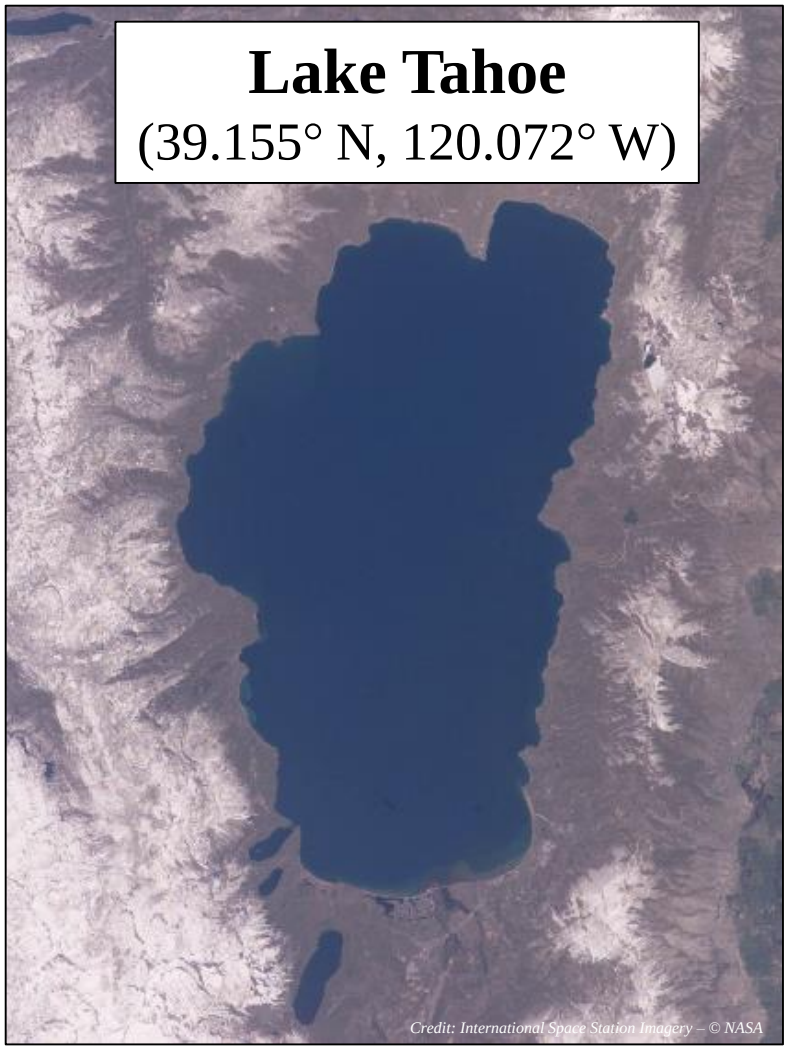
- Elevation: 1897 m
- Max. Depth: 501 m
- Avg. Depth: 300 m
- Surface Area: 490 km^2
- Climate: Dry-summer continental (Koeppen: Dsb)
- Oligomictic (avg. mixing every ~4 years)
- ~69 inlets, only 1 outlet (Truckee River)

❑ Issues

- ✓ Water Quality and Clarity
- ✓ Ecosystem Sustainability
- ✓ Tourism
- ✓ Economics
- ✓ Outdoor Recreation

❑ Facts

- ➢ Largest alpine lake in North America
- ➢ Second deepest lake in the United States
- ➢ Sixth largest by volume behind the Great Lakes



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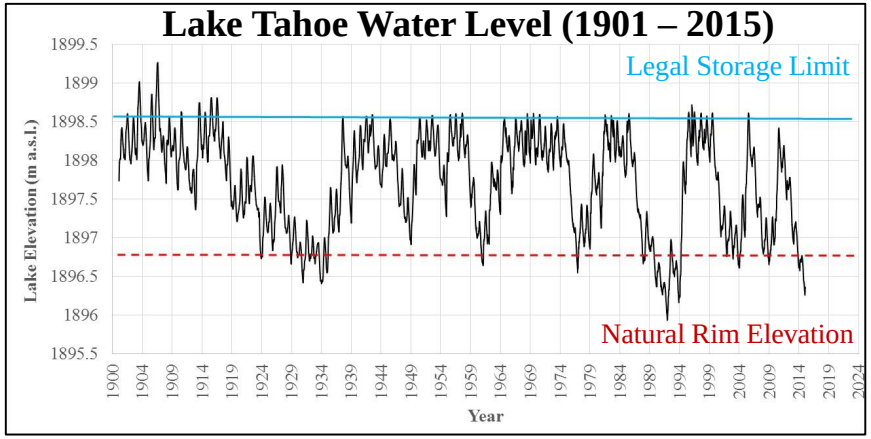
Motivation for the Study

Recently, reservoirs across the western United States have been experiencing extremely low water levels with water **demands increasing and supplies decreasing**.

(Fulp, 2005; Barnett and Pierce, 2008)

Motivation for the Study



Recently, reservoirs across the western United States have been experiencing extremely low water levels with water **demands increasing and supplies decreasing**.

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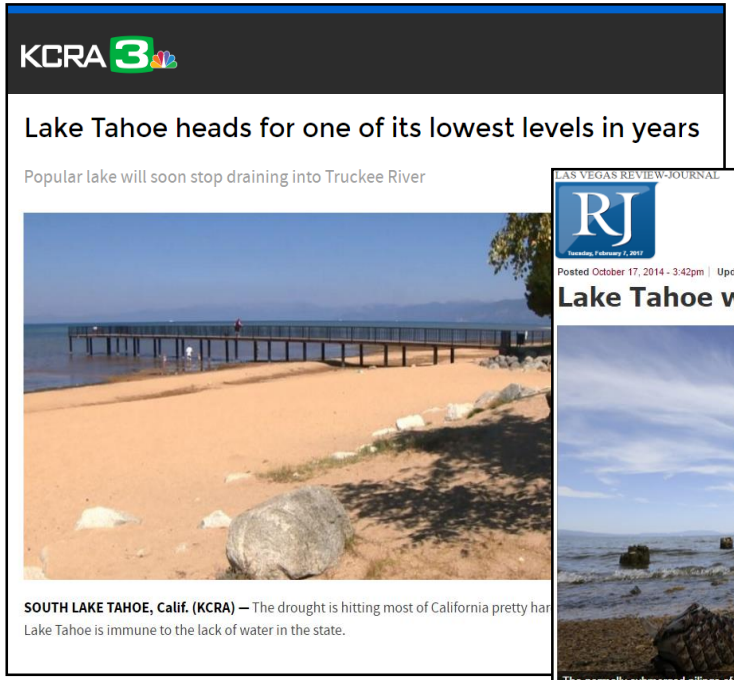
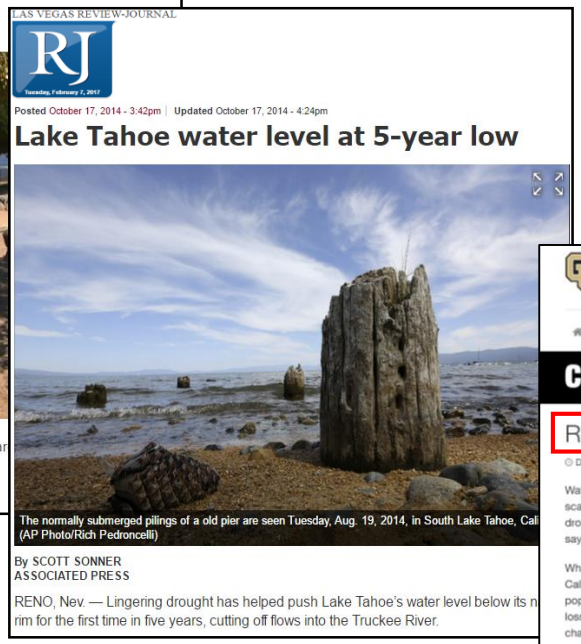
Open water evaporation is one of the most difficult surface energy/water fluxes to quantify, and is rarely directly measured in the natural environment.


KCRA 3

Lake Tahoe heads for one of its lowest levels in years

Popular lake will soon stop draining into Truckee River

SOUTH LAKE TAHOE, Calif. (KCRA) — The drought is hitting most of California pretty har
Lake Tahoe is immune to the lack of water in the state.


LAS VEGAS REVIEW-JOURNAL

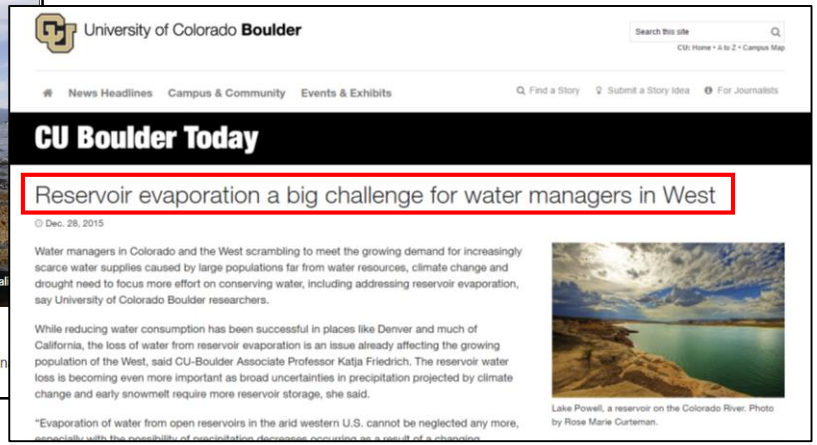
Posted October 17, 2014 - 3:42pm | Updated October 17, 2014 - 4:24pm

Lake Tahoe water level at 5-year low

The normally submerged pilings of a old pier are seen Tuesday, Aug. 19, 2014, in South Lake Tahoe, Cali
(AP Photo/Rich Pedroncelli)

By SCOTT SONNER
ASSOCIATED PRESS

RENO, Nev. — Lingering drought has helped push Lake Tahoe's water level below its n
rim for the first time in five years, cutting off flows into the Truckee River.


University of Colorado Boulder

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CU Boulder Today

Reservoir evaporation a big challenge for water managers in West

Dec. 28, 2015

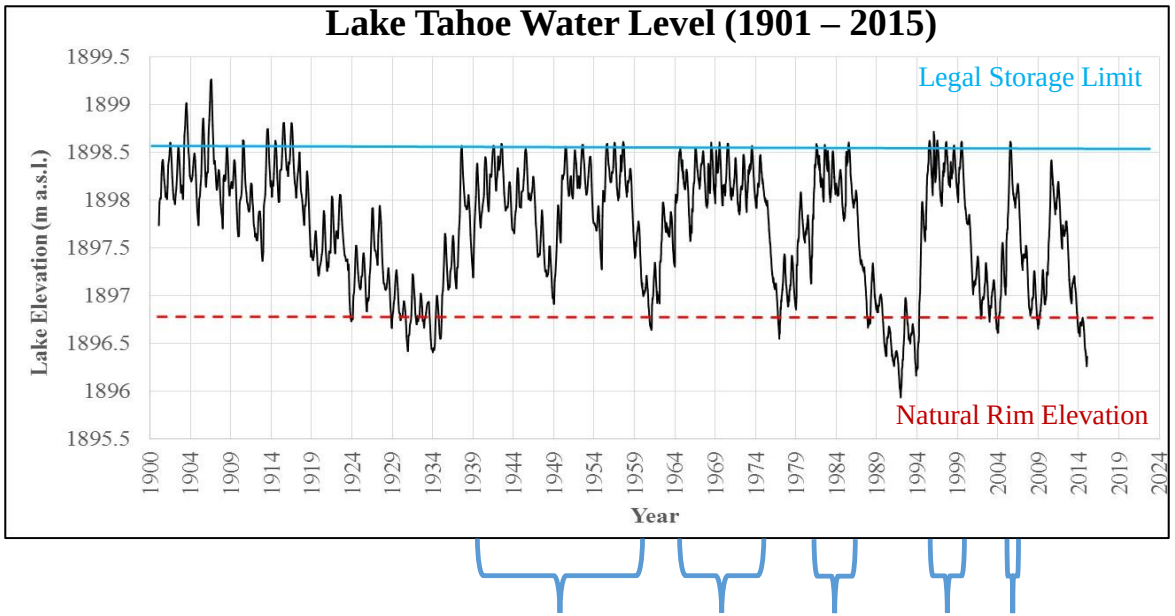
Water managers in Colorado and the West scrambling to meet the growing demand for increasingly scarce water supplies caused by large populations far from water resources, climate change and drought need to focus more effort on conserving water, including addressing reservoir evaporation, say University of Colorado Boulder researchers.

While reducing water consumption has been successful in places like Denver and much of California, the loss of water from reservoir evaporation is an issue already affecting the growing population of the West, said CU-Boulder Associate Professor Katja Friedrich. The reservoir water loss is becoming even more important as broad uncertainties in precipitation projected by climate change and early snowmelt require more reservoir storage, she said.

"Evaporation of water from open reservoirs in the arid western U.S. cannot be neglected any more,

Lake Powell, a reservoir on the Colorado River. Photo by Rose Marie Curteman.

Motivation for the Study



Duration of time when lake is at maximum capacity (i.e. Legal Storage Limit) has been decreasing since ~1940.

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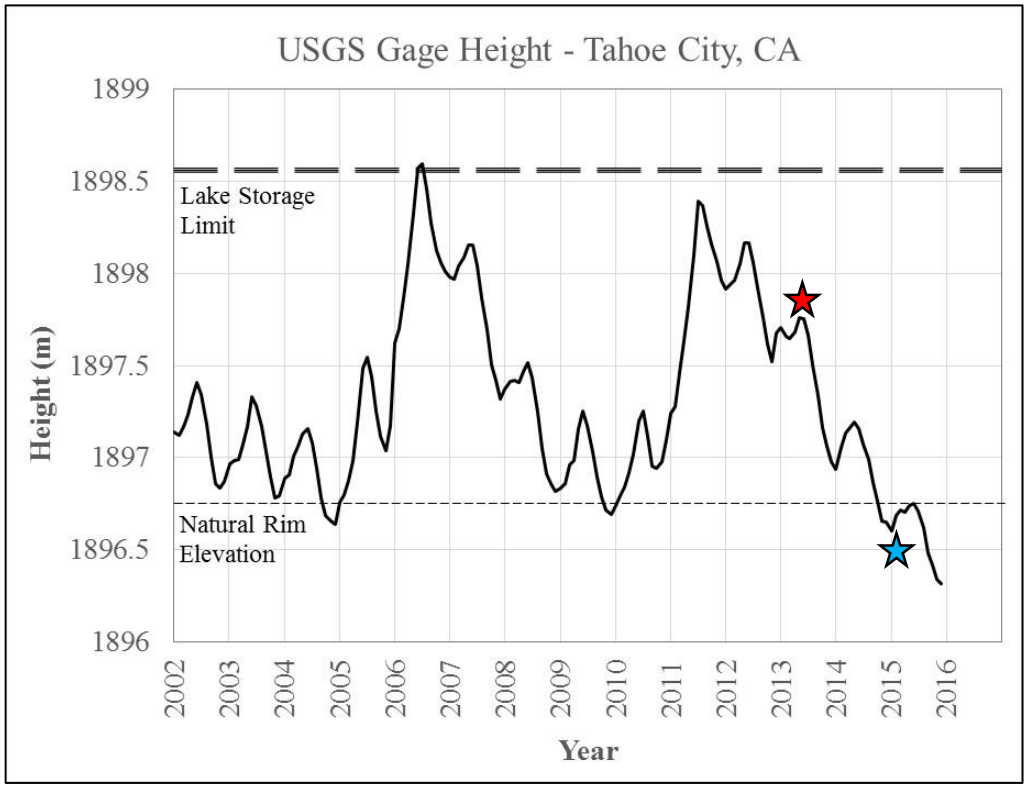
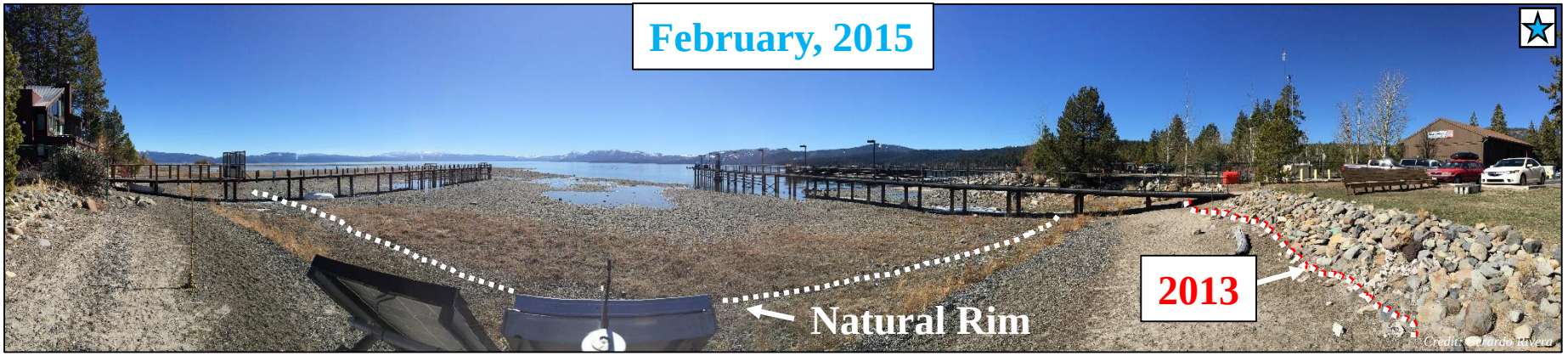
Motivation for the Study



What are the dominant factors controlling water level at Lake Tahoe?

How influential is evaporation in the overall water budget of Lake Tahoe?

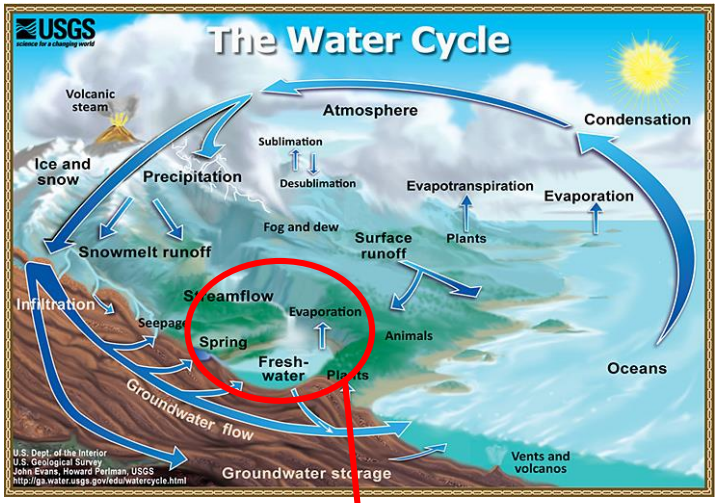


Methodology: Estimating Evaporation

- **Pan Evaporation**
  - Pan coefficient
- **Bowen Ratio Energy Balance (BREB)**
  - Net radiation, heat storage, inflow, outflow, humidity & temperature gradients
- **Eddy Covariance**
  - 3-D wind and water vapor
- **Water Balance**
  - inflow, outflow, groundwater in and groundwater out, diversions, and precipitation
- **Models**
  - Example: Complimentary Relationship Lake Evaporation (CRLE)
- **Mass Transfer/Bulk Aerodynamic**
  - Surface temperature, humidity, and wind speed over water

Water vapor flux from an open water body surface by way of turbulent diffusion as a function of **wind speed** and the **vapor pressure gradient** (Dalton, 1802)

Benefits: Low Cost, Minimal Data Requirements



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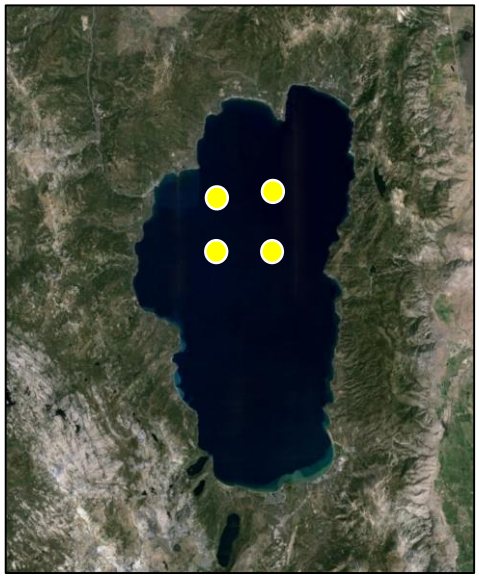
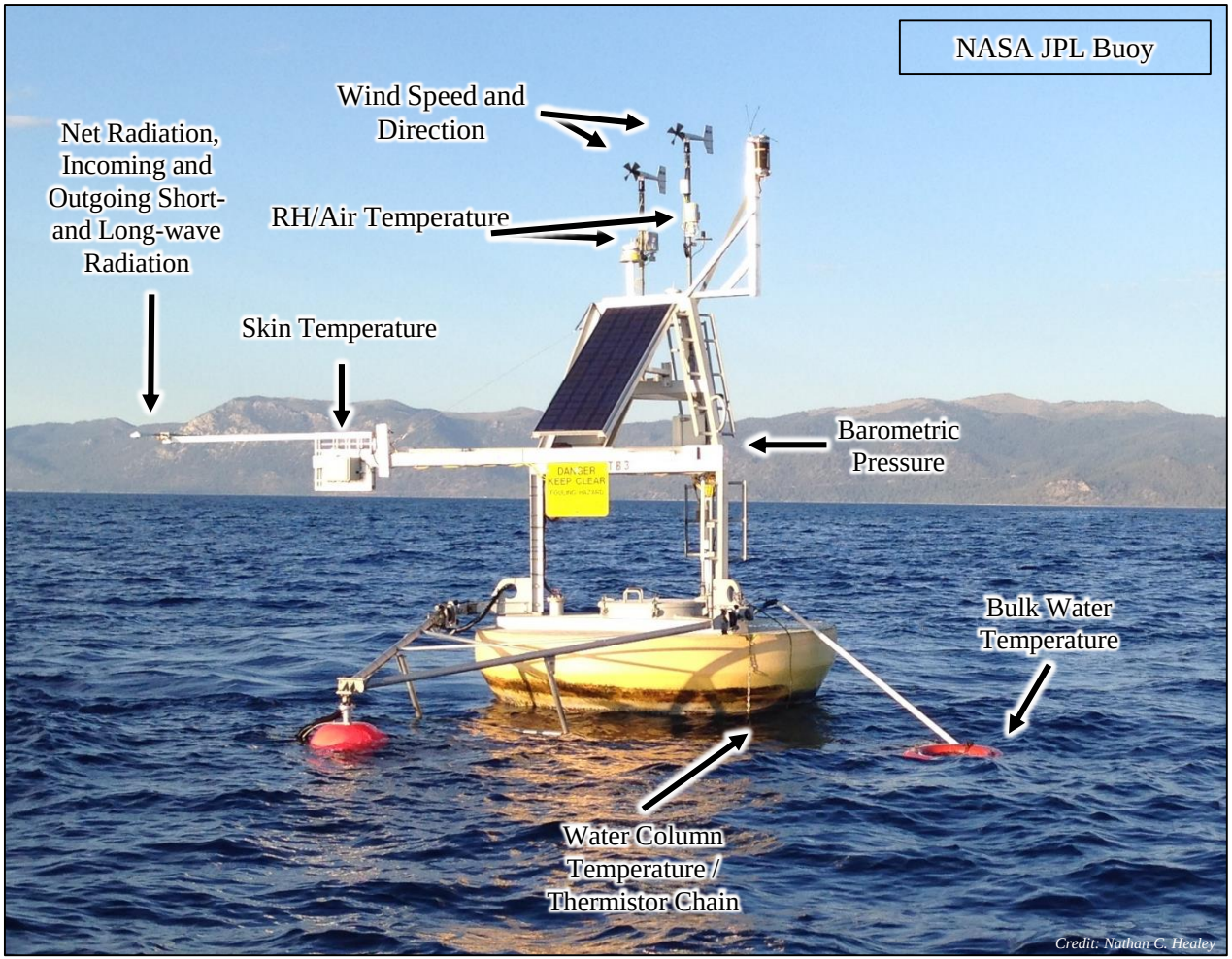
Methodology: Buoys at Lake Tahoe

- Deployed in 1999
- Continuous Measurements (every 5-min)



Custom JPL Radiometers

- 8-14 μm
- Accuracy: ± 0.08 °C
- Calibrated at JPL with NIST-traceable stirred water bath blackbody



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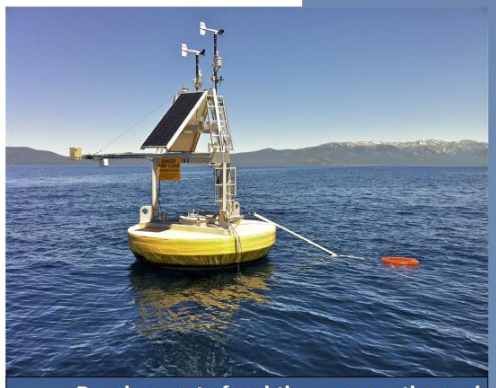
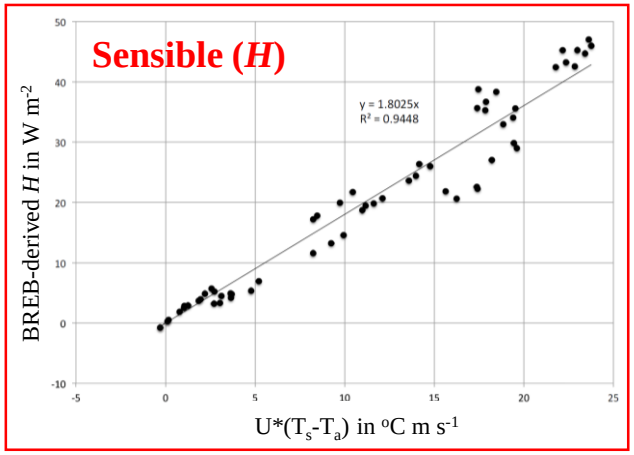
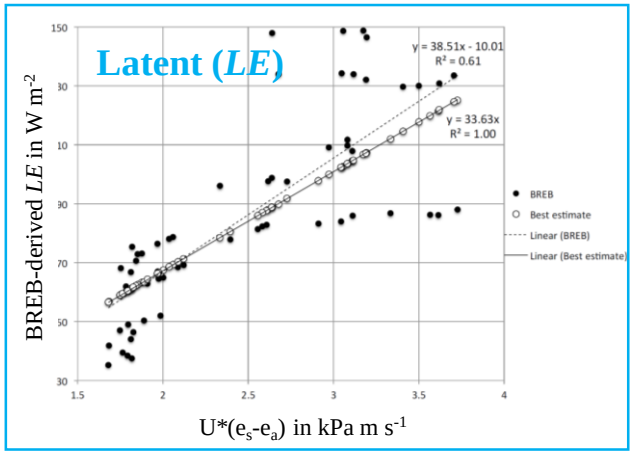
Evaporation Estimation at Lake Tahoe: "Hybrid Method"

Bowen Ratio Energy Balance (BREB) and Mass Transfer



16 different time periods (42-391 days) for BREB analysis using 2011-2012 data





"Hybrid Method"

BREB estimates of *H* generate estimates of *LE* using the Bowen Ratio.

$$\beta = \gamma \frac{\overline{U(T_s - T_a)}}{\overline{U(e_s - e_a)}}$$

$$\beta = \frac{H}{LE}$$

Mass Transfer

$$H = C_H \cdot U(T_s - T_a)$$

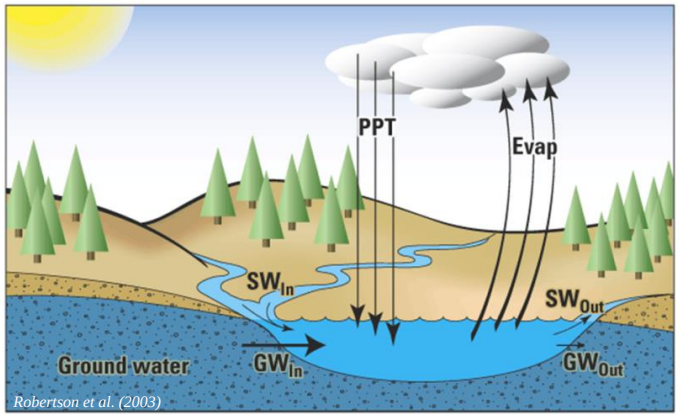
$$LE = C_E \cdot U(e_s - e_a)$$

γ : psychrometric constant (m s^{-1})
U : wind speed (m s^{-1})
e_s: saturation vapor pressure of water (kPa)
e_a: vapor pressure of air (kPa)
T_s: surface water temperature (^{o}C)
T_a: air temperature (^{o}C)

(Lenters and Soylu, 2014; Lenters *et al.*, 2005)

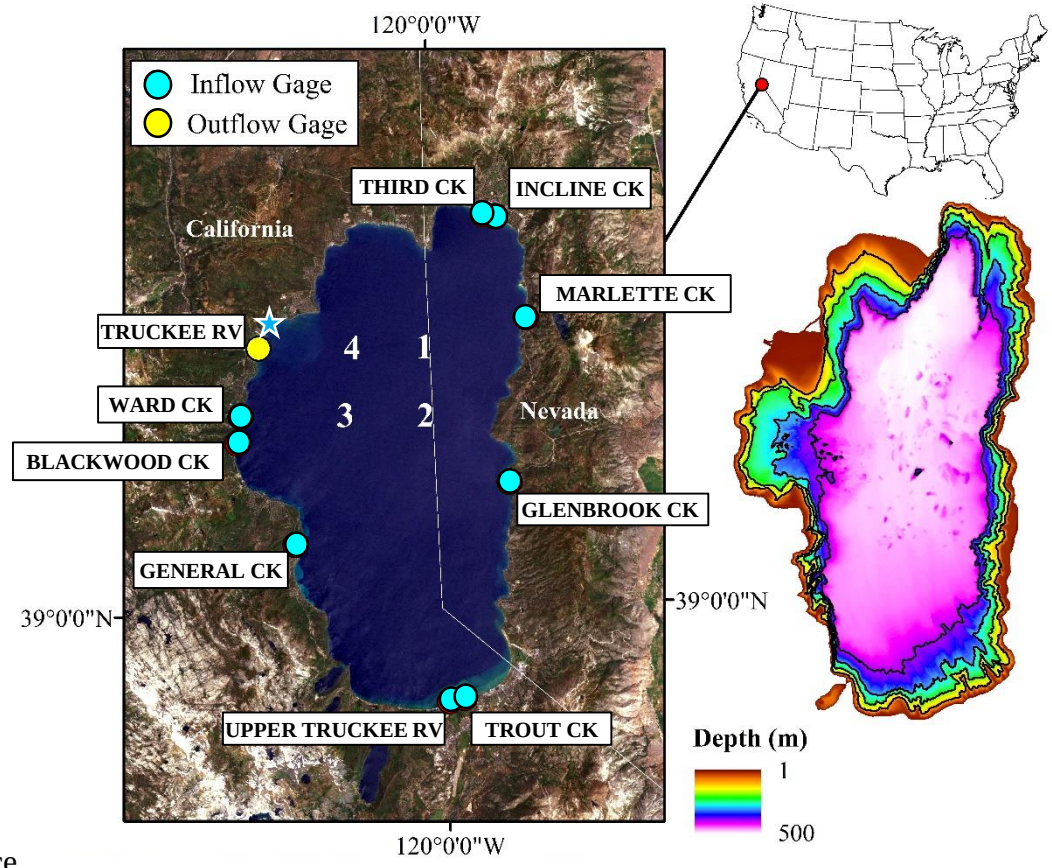
Methodology: Water Balance

$$(PPT + SW_{in} + GW_{in}) - (Evap + SW_{out} + GW_{out}) = 0$$



Assume groundwater exchange is negligible

where:
PPT = precipitation
SW$_{in}$ = inflow
SW$_{out}$ = outflow
Evap = evaporation (buoys labeled 1-4)



Precipitation data is from the National Weather Service COOP station at Tahoe City

Inflow and **outflow** data are from all USGS gaging stations around Lake Tahoe.

Methodology: Water Balance

$$(PPT + SW_{in} + \cancel{GW_{in}}) - (Evap + SW_{out} + \cancel{GW_{out}}) = 0$$

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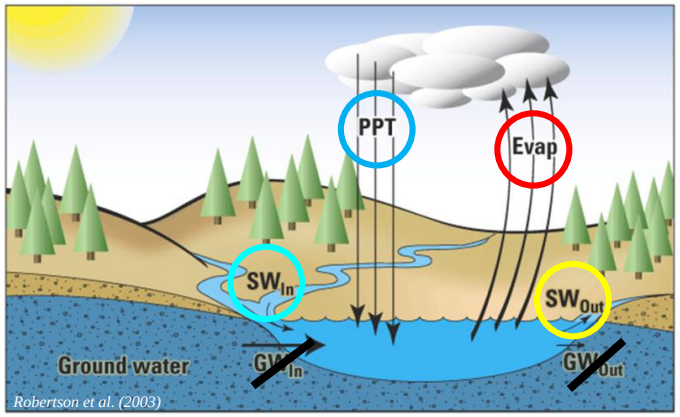

Assume groundwater exchange is negligible

where:

- PPT = precipitation ★
- SW_{in} = inflow ●
- SW_{out} = outflow ●
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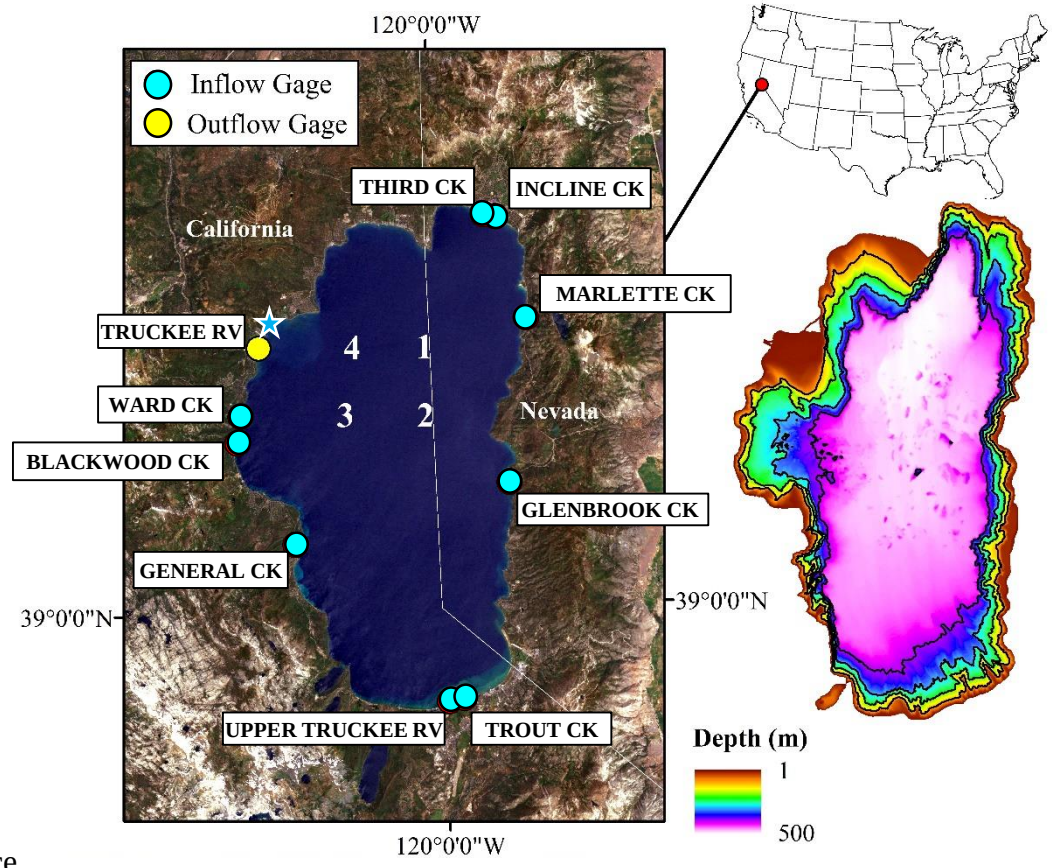


Precipitation data is from the National Weather Service COOP station at Tahoe City

Inflow and **outflow** data are from all USGS gaging stations around Lake Tahoe.

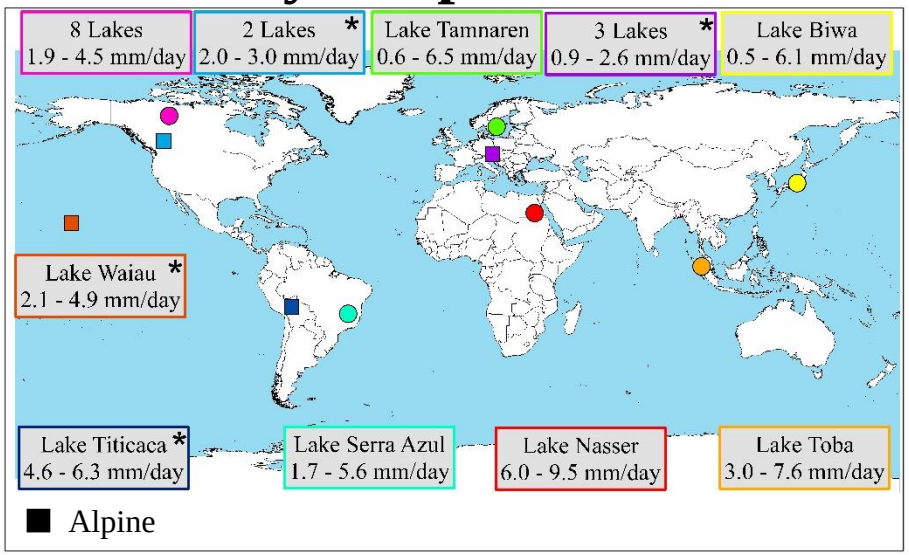
Results and Discussion: Diel and Daily Evaporation

- Computed rates at Lake Tahoe are comparable with other **alpine lakes** around the world.
  - ➢ Range: 0.9 – 6.3 mm day^{-1}

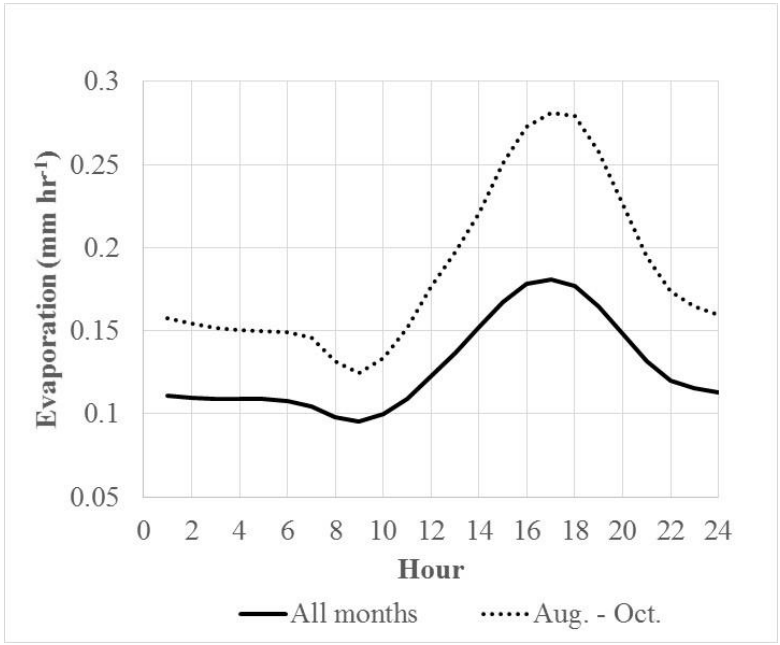
(dos Reis and Dias, 1998; Elsawwaf *et al*., 2010; Ikebuchi *et al*., 1988; Gibson *et al*., 1996; Gibson, 2002; Sene *at al*., 1991; Saxena, 1996; Kittel and Richerson, 1978; Patrick and Kauahikaua, 2015; Roy and Hayashi, 2008)

- Other estimates of Evaporation at Lake Tahoe:
  - ➢ Range: 2.5 – 3.0 mm day^{-1}

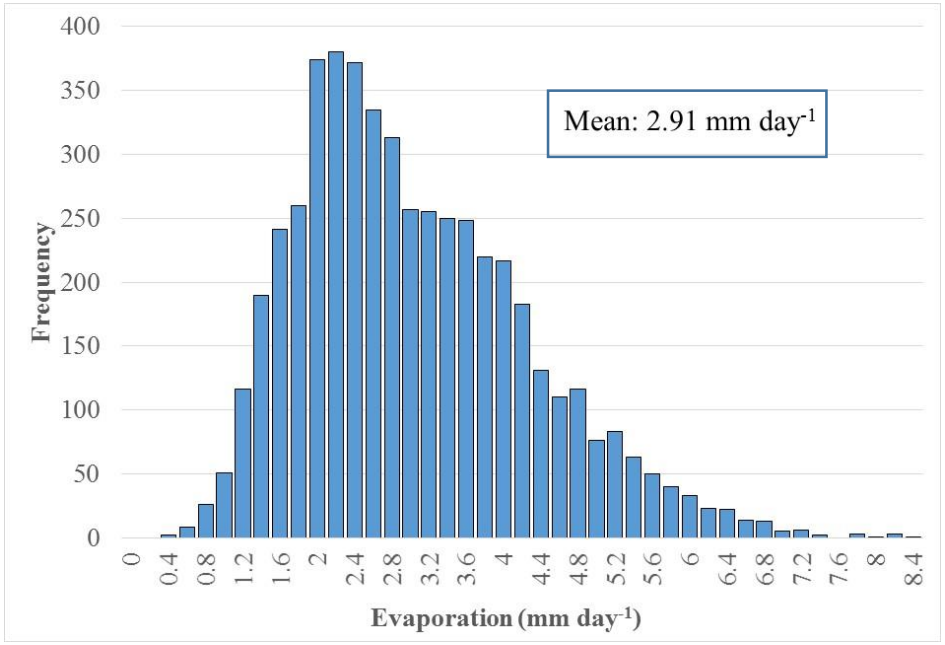
(Dugan and McGauhey, 1974; Myrup et al., 1979; Trask, 2007; Huntington and McEvoy, 2011)



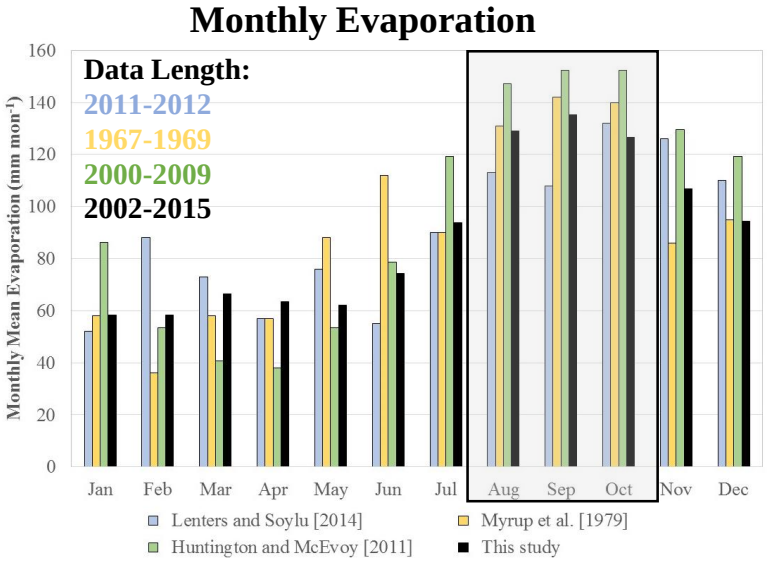
Diel Cycle of Evaporation (2002 – 2015) Lake Tahoe, CA/NV



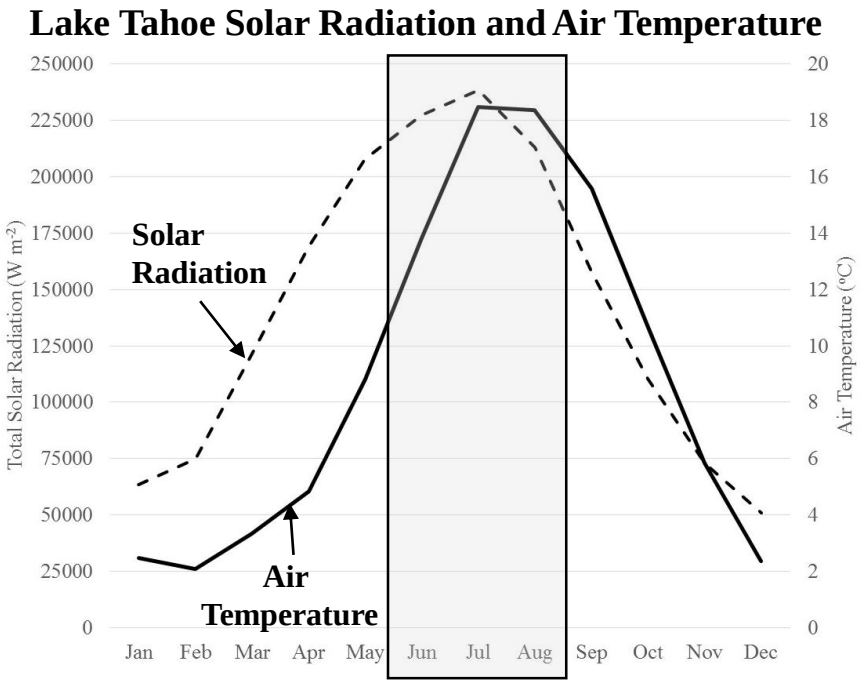
Daily Evaporation (2002 – 2015) Lake Tahoe, CA/NV

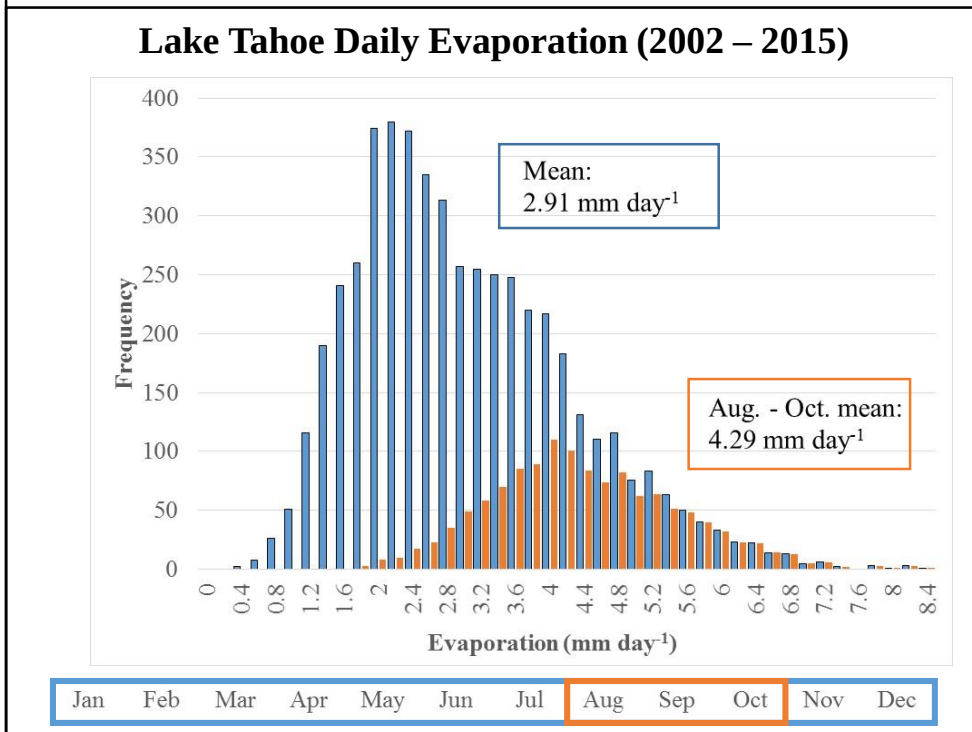


Results and Discussion: Daily and Monthly Evaporation



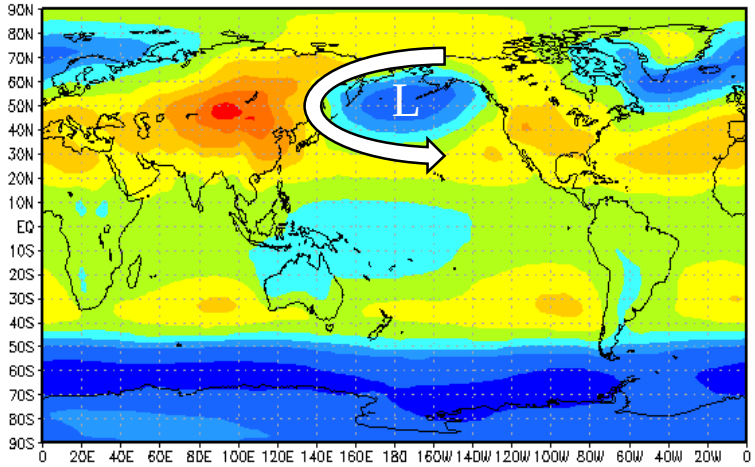
Due to the high thermal inertia of water, peak evaporation occurs between August and October; lagging behind peak solar radiation and air temperature.

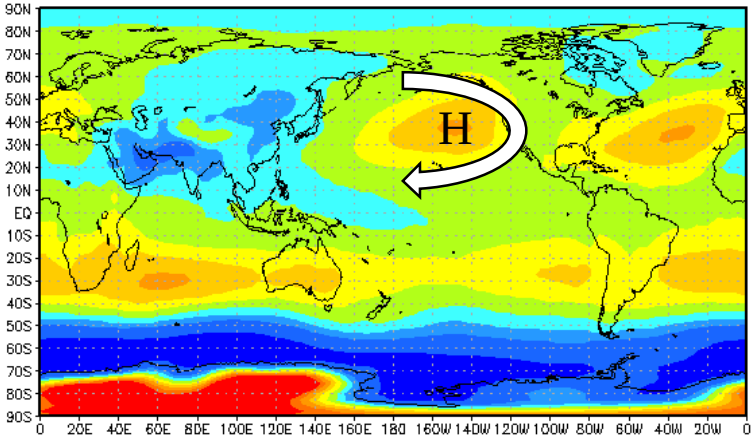




Results and Discussion: Seasonal Evaporation

Winter = Onshore Flow, Wet (Increasing Precipitation) = Water Level Rises

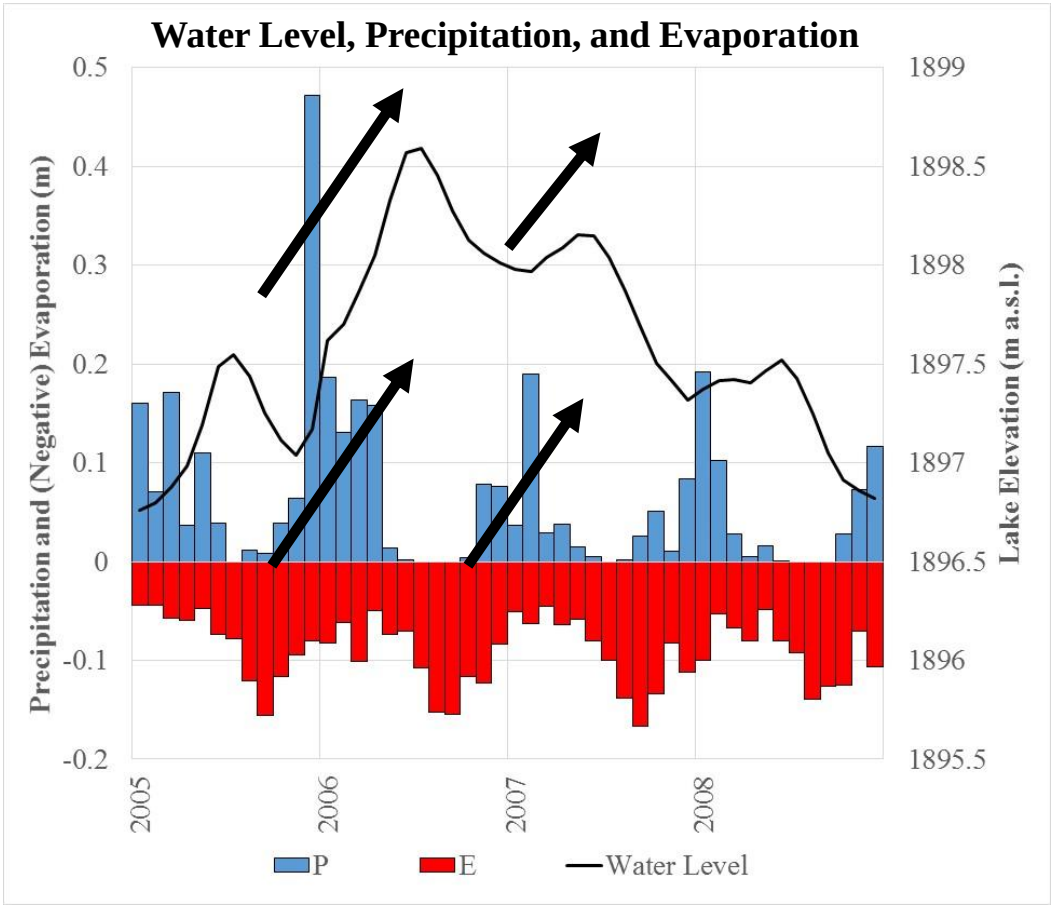




Sea Level Pressure (mb)

990 1000 1005 1010 1015 1020 1025 1030 1035

(Images courtesy of NOAA)



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Results and Discussion: Seasonal Evaporation

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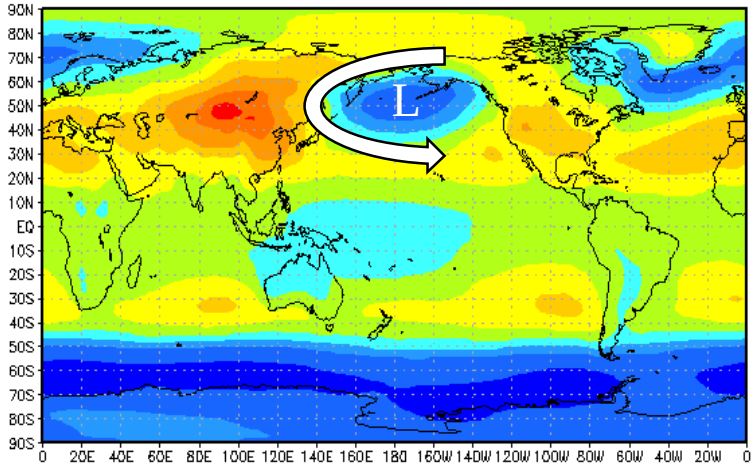
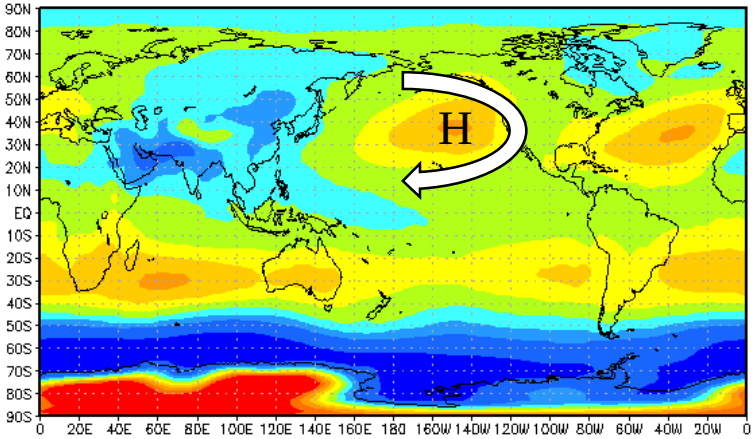


Summer = Offshore Flow, Dry (Increasing Evaporation) = Water Level Falls



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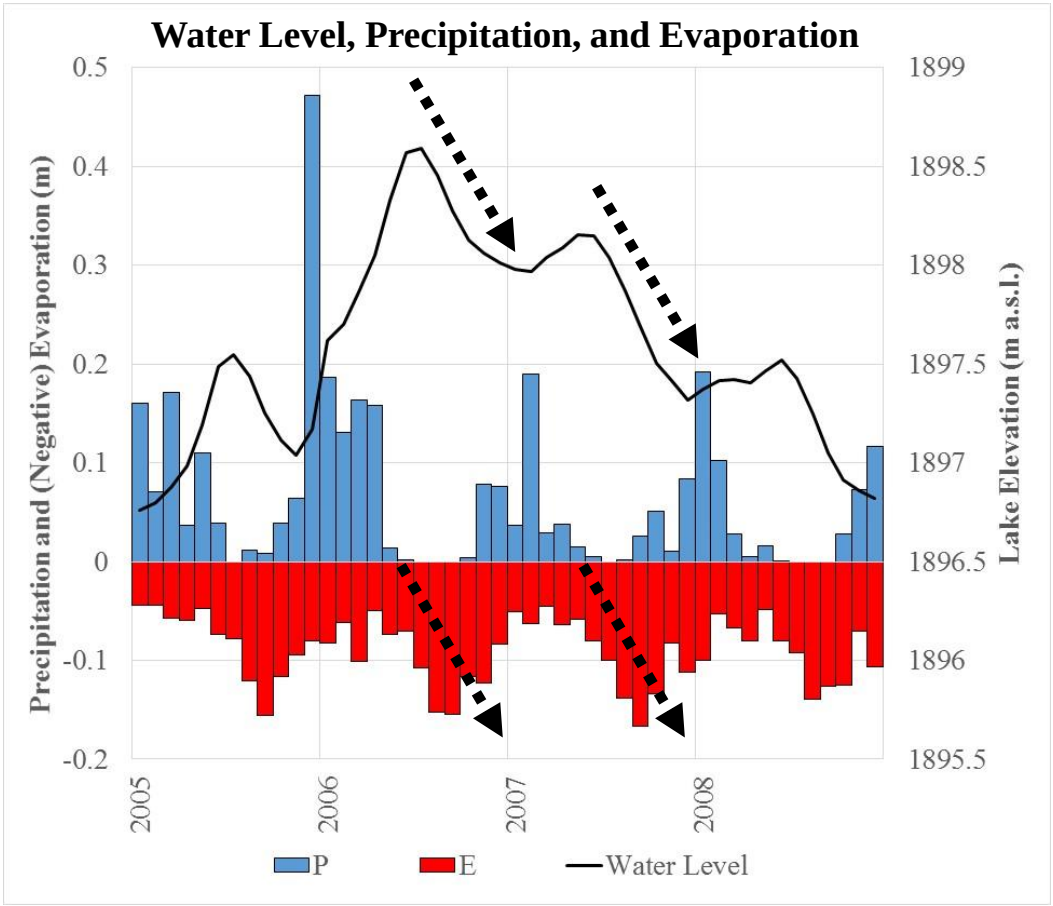

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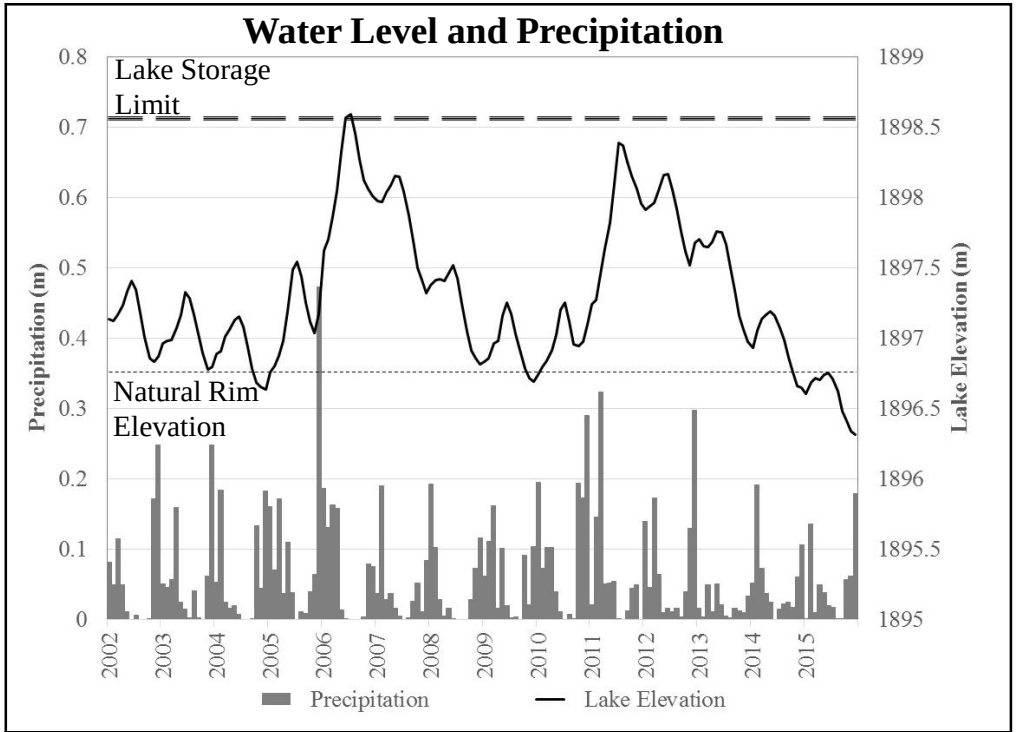
Results and Discussion: Water Level, Precipitation, Evaporation

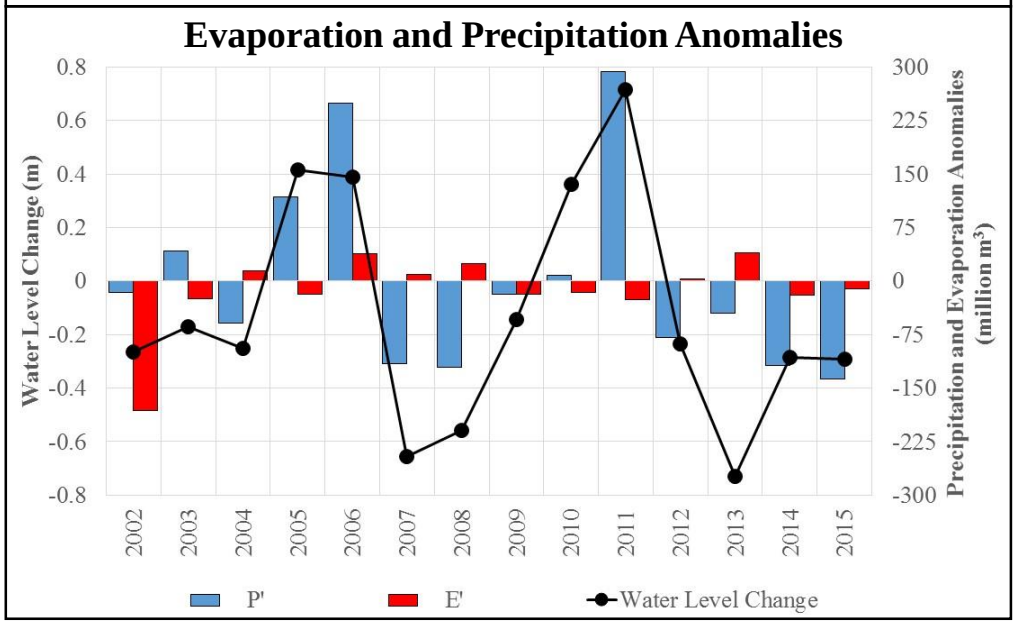
Precipitation patterns at Lake Tahoe are seasonally wet in winter, and dry in summer.

Water levels dropped below the natural rim in 2005, 2010, 2014-2015.

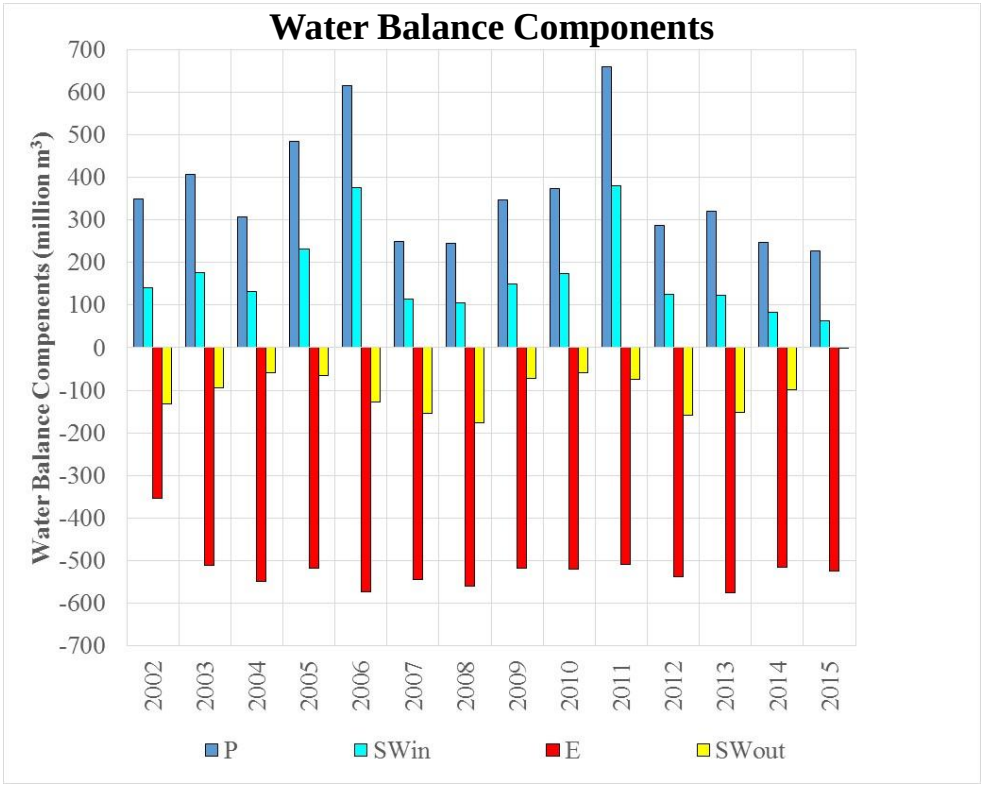
Anomalously high **precipitation** leads to **higher** lake levels

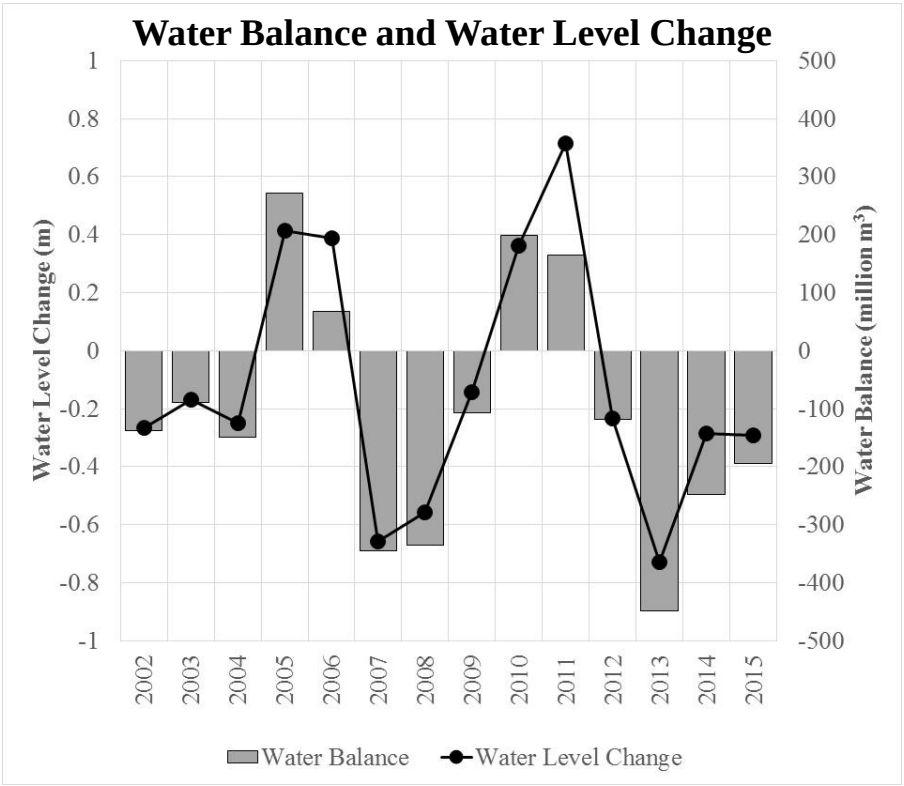
Anomalously high **evaporation** leads to **lower** lake levels.



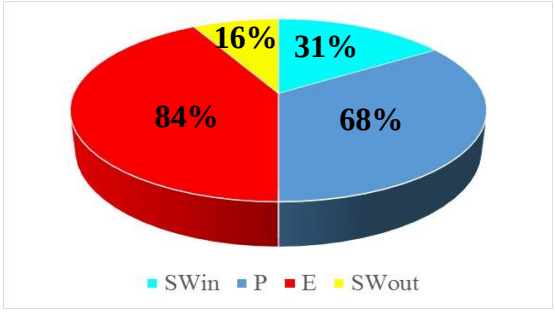


Results and Discussion: Annual Water Balance





Note: Water added (P and SWin) are shown as positive values, and water removed from the lake (E and SWout) are shown as negative values.



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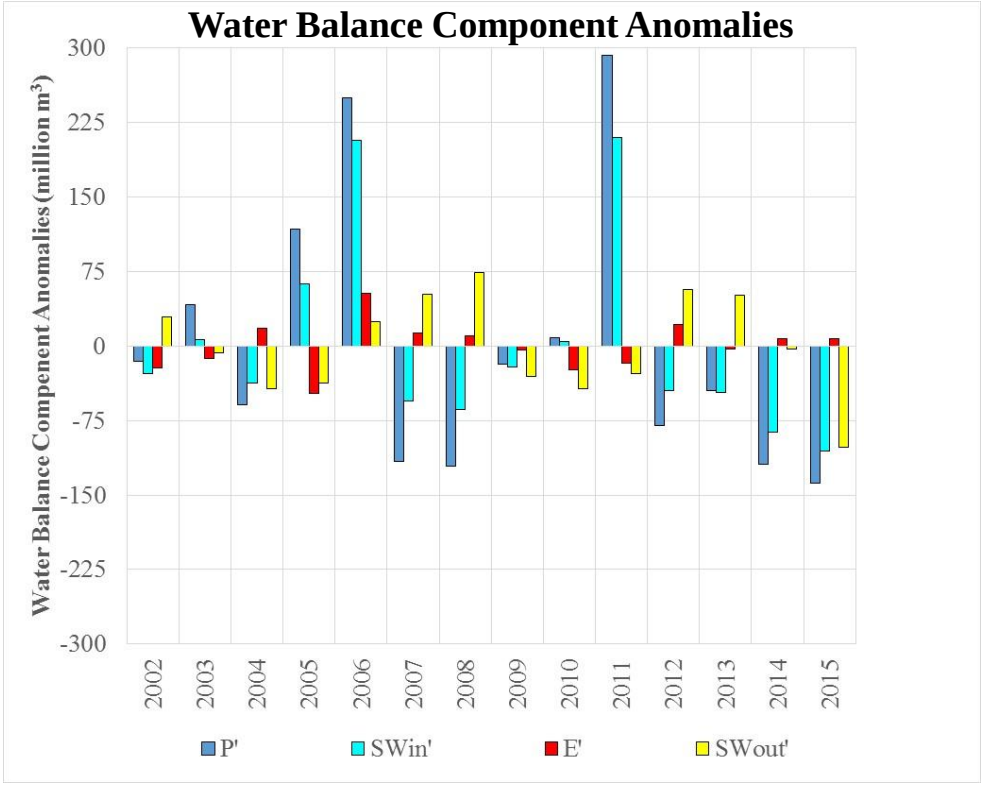
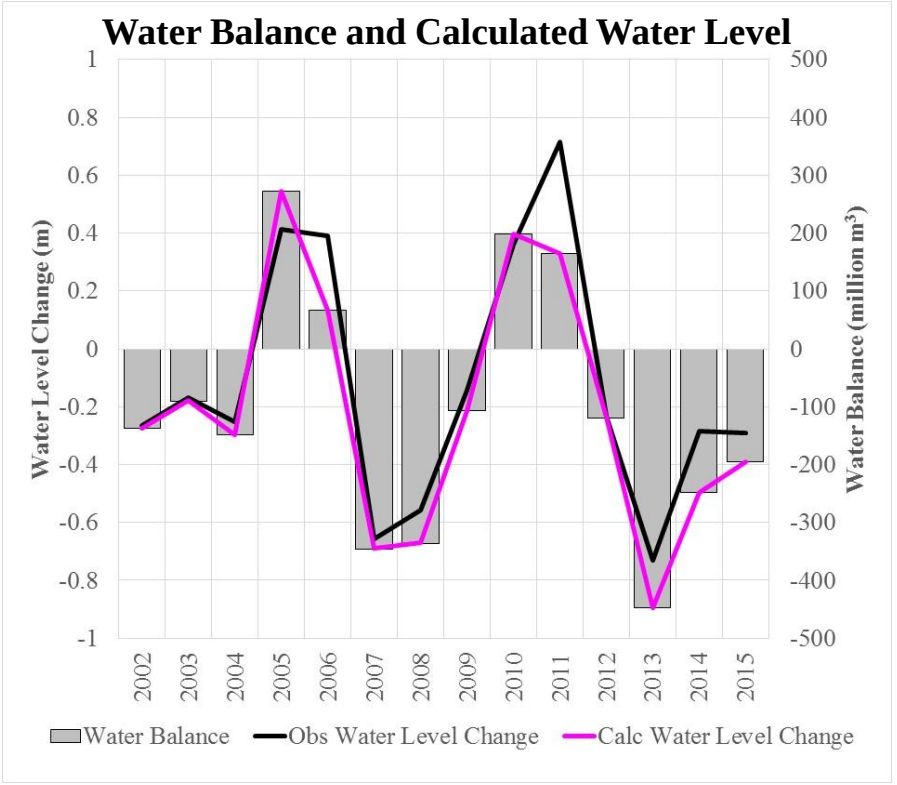
Results and Discussion: Annual Water Balance

Calculated water level change based on water balance:
Very close agreement with observations, with a few exceptions



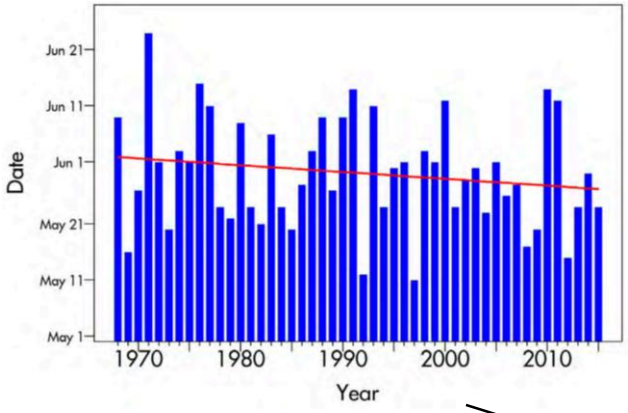


Potential Reasons for discrepancies in Calculated Water Level Change:

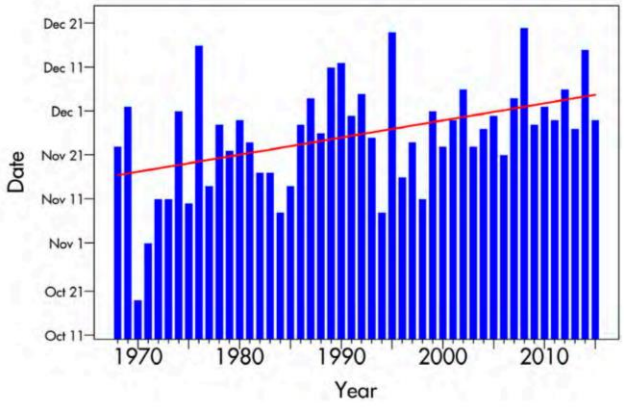
- Inflow measurement error
  ~69 inlets and only 10 USGS gages
- Precipitation measurement error
- Evaporation estimation error
- Diversions for municipalities
  ex. South Lake Tahoe, Tahoe City, etc.
- Diversions for commercial uses
  ex. Golf courses

Results and Discussion: Stratification

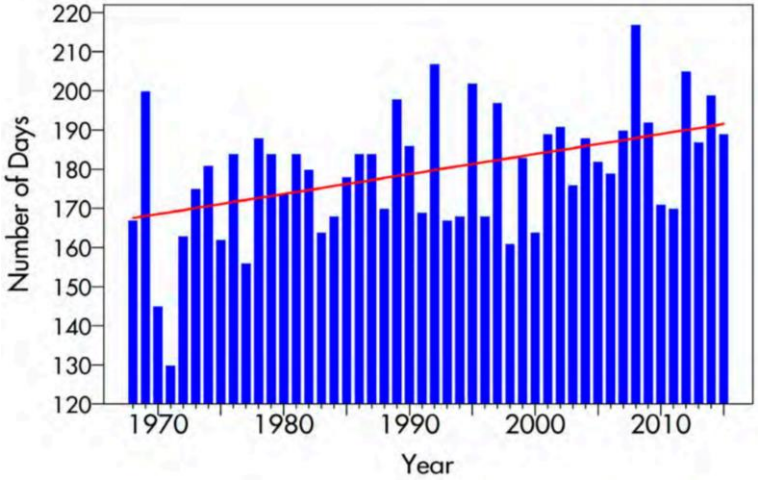
Beginning of Stratification



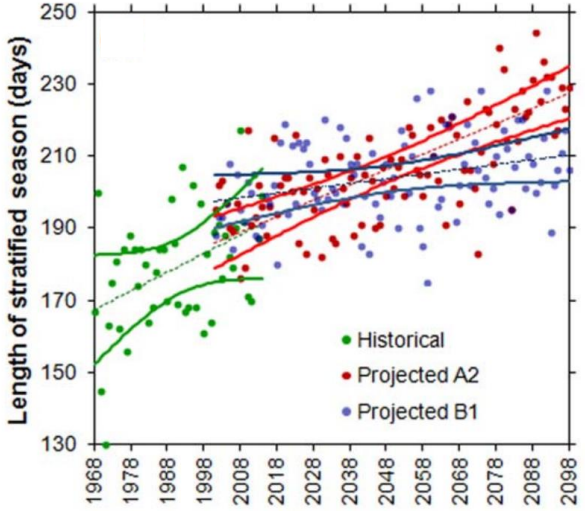
End of Stratification



Stratification Duration



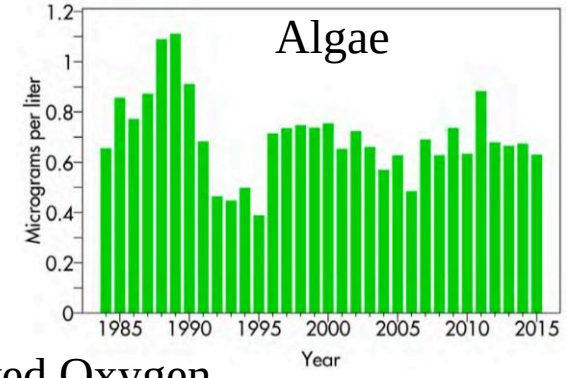
Future Projections of Stratification Duration

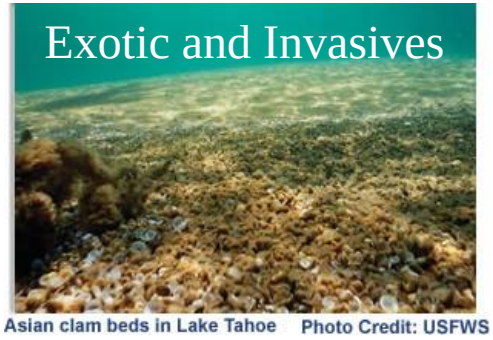


Longer stratification seasons = warmer lake water surface temperatures = increased evaporation

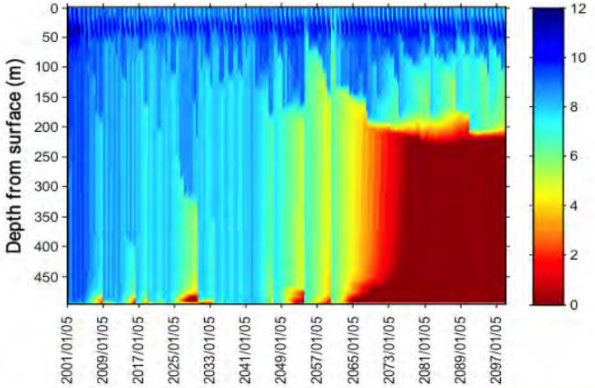
(TERC, 2015; Sahoo *et al.*, 2016)

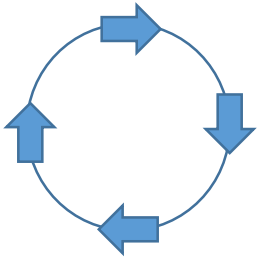
Results and Discussion: Lake Ecology

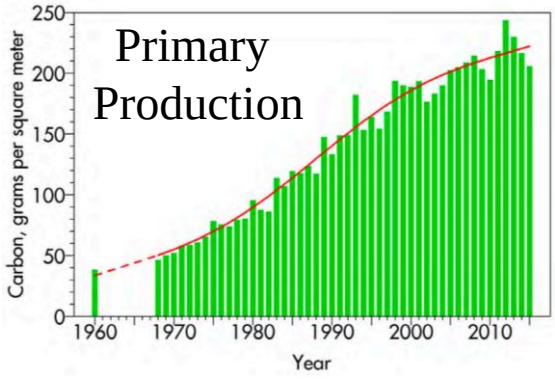


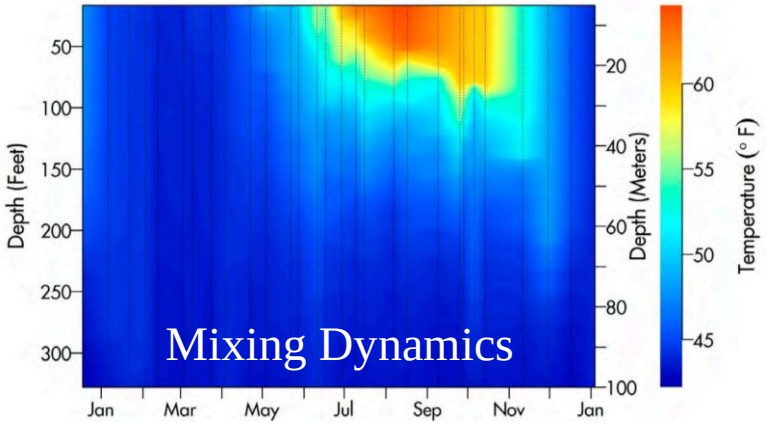


Dissolved Oxygen









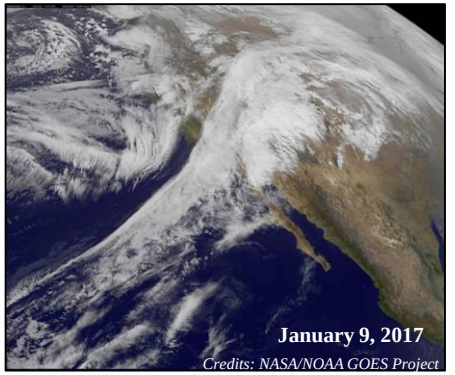
What we can expect:

- Changes in fish species composition.
- Less dissolved organic carbon and oxygen – more visible light and more UV radiation penetration.
- More weed growth – blue green algae growth.
- Longer stratification will alter mixing dynamics

(TERC, 2015)

Recent Drought Relief

January 2016
"Pineapple Express"



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LEGENDARY ACTOR JOHN HURT, KNOWN FOR 'ALIEN,' 'HARRY POTTER' AT 77

Storms Have Added 33.6 Billion Gallons of Water to Lake Tahoe This Year

POSTED 9:50 AM, JANUARY 10, 2017, BY TRACY BLOOM, UPDATED AT 11:05AM, JANUARY 10, 2017

A series of winter storms early this year has been good news for Lake Tahoe, which has gained about 33.6 billion gallons of water since Jan. 1, according to the National Weather Service.

A view of snow-capped mountains, Lake Tahoe, and the historic Cal-Neva Resort & Casino. (Credit: Allen J. Schaben / Los Angeles Times)

The lake has also risen nearly a foot since the start of the year.

"For reference: An average household of 4 people use 1 acre/foot of water per year," the weather service stated in a graphic that showed the latest figures for the lake.

The amount of water is welcome relief at the lake, where levels reached record levels a few years ago amid the ongoing California drought, the Los Angeles Times reported.

Forecasters expect more periods of heavy rain and snow to hit the region through midweek as another powerful storm takes aim at the northern part of the state.

Dangerous and potentially life-threatening blizzard conditions are expected in the Sierra, prompting the Weather Service to issue a blizzard warning that will expire on Wednesday morning.

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Los Angeles Times

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Weeks of rain are rapidly reviving California's drought-ravaged lakes

Recent storms and increased snowpack have contributed to rising water levels at Mono Lake. (Brian van der Brug / Los Angeles Times)

By Louis Sahagun, Matt Stevens and Paige St. John - Contact Reporters

JANUARY 11, 2017, 5:00 AM | REPORTING FROM MONO LAKE, CALIF.

Leaning against a wooden rail, environmental activist Geoffrey McQuilkin took stock of a parched geological wonderland that had been altered by a weekend deluge.

The air was still thick with moisture, and this lake's tributaries were cascading down from surrounding mountains, swollen by cargoes of fresh snowmelt and rain. Frothy whitecaps and wavelets lapped over grass meadows that had been dry ground only a week ago. The lake's famous tufa formations — for so long a symbol of California's lack of water — were

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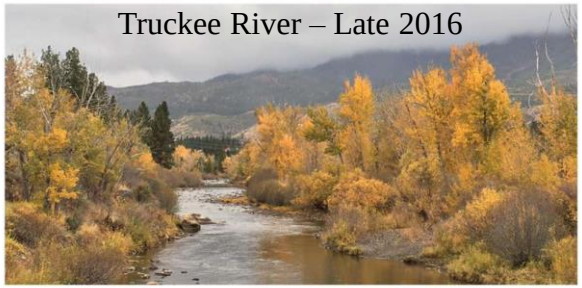
Truckee River – Late 2016



Truckee River – January 2017

Spirits rise as Lake Tahoe water level does, too

Lake Tahoe reached an important milestone over the weekend. The lake level rose to 62-hundred-23 feet above sea level, which is Tahoe's natural rim.

George Warren, KXTV 12:20 PM. PDT April 12, 2016

Lake Tahoe reached an important milestone over the weekend. The lake level rose to 6,223 feet above sea level, which is Tahoe's natural rim.

There's a much missed sound babbling through Tahoe City.

Lake Tahoe rose up to its natural rim over the weekend, and as of Monday, water is trickling into the Truckee River.

It may not seem very impressive, but the fact that any water at all is flowing is a major accomplishment.

The lake last reached its rim 10 months ago, and then only stayed there for five days before dropping back down well below the dam.

"Well, I'm glad to see it's up to the gates now," said Tahoe City resident Roger Schaefer. "What's it been like? Sand. Dry. Lots of extra space along the lake."

Truckee's two rafting companies never even got into the water last summer.

So while the lake reaching the rim is encouraging, they need quite a bit more to start floating, said Richard Courcier of Truckee River Rafting.

"Yes, everyone's all excited – and it is exciting – but if you look at the river, it's just like a garden hose going down," Courcier said. "You need to get more elevation above the rim to

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Conclusions

In western USA: demand for water is increasing and supply is decreasing

- Need for improved water balance estimates

What are the dominant factors controlling water level at Lake Tahoe?

- Precipitation and Evaporation

How influential is evaporation in the overall water budget of Lake Tahoe?

- Accounts for roughly 80% of water losses.
- Average annual water lost to evaporation:
  - ❖ **535.8 million m^3**
  - ❖ **434,000 acre ft.**
  - ❖ **141.5 billion gallons = ~800 thousand households**

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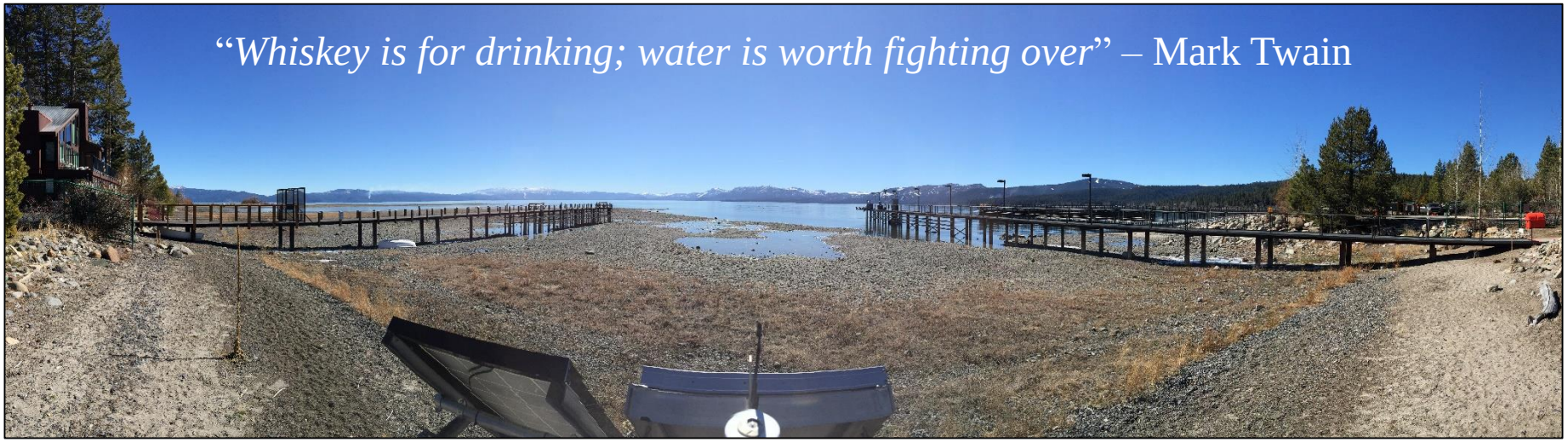
Thank You!



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